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Modelling the X-Ray Emission from the Magnetar Wind Nebula around Swift J1834.9-0846

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The extended X-ray emission around Swift J1834.9-0846 observed with *XMM-Newton* was recently identified to be the first magnetar wind nebula. The high X-ray efficiency of this nebula indicates that it may not be predominately powered by rotational energy of magnetar, but its internal magnetic energy released during burst activities. Similar to the case of rotation-powered pulsars, the energetic particle outflow injected from the magnetar propagates downstream of the termination shock and produces non-thermal radiations through interactions with the interstellar medium. The observed photon index softening towards the outer nebula was attributed to the cooling of relativistic electrons, which could provide useful information about particle transport in the nebula. In this work, we reanalyzed the *XMM-Newton* observations taken in 2014, and then developed a spatially dependent model to simulate the X-ray emission from the magnetar wind nebula. The fitting results favor the magnetic origin of the magnetar wind nebula. We also found that the observations could be well explained by the model without particle diffusion, indicating advection dominates particle transport in this nebula.

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1. Introduction

Pulsars are rapidly spinning, highly magnetized neutron stars. The relativistic pulsar wind blowing out from pulsar's magnetosphere would terminate by interacting with its environment [2]. It is generally believed that particles could be accelerated to relativistic energies at the termination shock (TS). The accelerated particles propagate downstream of the shock, and produce multi-wavelength electromagnetic emissions through synchrotron and inverse Compton (IC) radiation, which is observationally seen as pulsar wind nebula (PWN). PWNe are considered to be powered by the rotational energy of pulsars,which are referred to rotation-powered pulsars (RPPs).

Different from the RPPs, magnetars are a class of neutron stars with much higher surface magnetic field. Magnetars usually have longer spin periods than RPPs, so their spin-down luminosities are lower than that of RPPs ($L_{\mathrm{s}} = 4\pi^2 I\dot{P}/P^3$), which may be the reason why the wind nebulae around magnetars (MWN) are hardly detected. However, the situation has changed since the discovery of the magnetar Swift J1834.9-0846 when it burst in 2011 [3]. The post-outburst observations have shown an extended X-ray emission around the magnetar, which was supposed to originate from the wind nebula of Swift J1834.9-0846 [4].

The wind nebula around Swift J1834.9-0846 has some similar features to PWN. The size of the nebula is about 2 pc assuming a distance of 4 kpc if Swift J1834.9-0846 is spatially associated with the supernova remnant (SNR) W41. Its spectrum can be best fit by an absorbed power-law, with an average photon index of $\Gamma = 2.2 \pm 0.2$. The radial distribution of photon index shows a softening trend in the MWN, which is 1.4 in the inner nebula and 2.5 near the outer region [4]. The spectral index softening is attributed to the cooling of relativistic electrons.

Despite many similarities, the wind nebula of Swift J1834.9-0846 has a noticeable difference from the ordinary PWN: the X-ray efficiency of the MWN is very high ($\eta_{\mathrm{X}} \sim 0.1$), about two orders of magnitude larger than that of PWN. Granot et al. argued that the rotational power of Swift J1834.9-0846 is insufficient to explain the X-ray luminosity of the diffuse emission, and other energy source is required, such as the internal magnetic energy of the magnetar [5]. On the other hand, Torres et al. proposed that the MWN is currently under compression by the reverse shock of supernova remnant (SNR), which could enhance the magnetic field and thus the synchrotron X-ray emission inside the MWN [6].

In this contribution, we studied the X-ray emission of the MWN in detail. We developed a spatially dependent model to investigate particle transport in the wind nebula of Swift J1834.9-0846 and its energetics. For simplicity, we assume the magnetar wind nebula around Swift J1834.9-0846 is still in its free expansion phase. Our simulations show that the data cannot be simultaneously fitted if the wind nebula is only powered by magnetar spinning-down, whereas it could be well explained with the additional injection of magnetic energy of magnetar. By fitting the intensity profile and photon index profile, we also find that particle transport in the nebula is mainly dominated by advection.

2. Theoretical Modelling

Since magnetars share many similar properties with pulsar, it is convenient for us to extend the model developed for PWNe to MWNe.

2.1 Dynamical Evolution

Magnetars continuously inject their rotational energy in the form of relativistic wind, which interacts with the surrounding medium and forms magnetar wind nebula. The radius of the termination shock between the magnetar wind and the nebula could be estimated by equating the pressure inside the nebula and the ram pressure of the relativistic wind [2]:

$$R_{\rm ts}(t) = \sqrt{\frac{L(t)}{4\pi c P_{\rm ts}(t)}}, \tag{1}$$

where $P_{\rm ts}$ is the pressure inside the nebula at the position close to the termination shock.

The outer boundary of the nebula could be treated as a thin shell, and the evolution of its radius is determined by the pressure on the both side [7]:

$$\frac{d}{dt}\left[M_{\rm sw}(t)\dot{R}_{\rm mwn}(t)\right] = 4\pi R^2_{\rm mwn}(t)\left[P_{\rm in}(t) - P_{\rm out}(t)\right], \tag{2}$$

where $M_{\rm sw}$ is the mass of the swept material surrounding MWN.

The evolution of magnetic field in the MWN is also needed in order to calculate the synchrotron emission of relativistic particles [1]:

$$\frac{dW_{\rm B}(t)}{dt} = \eta_{\rm B} L(t) - \frac{W_{\rm B}(t)}{R_{\rm mwn}(t)}\frac{dR_{\rm mwn}(t)}{dt}, \tag{3}$$

where $\eta_{\rm B}$ is the fraction of the total injected energy converted to the magnetic energy in the nebula.

2.2 Particle Transport Equation

Particles accelerated at termination shock will propagate downstream via advection and diffusion, which could be described by [8, 9]:

$$\frac{\partial N}{\partial t} = D\frac{\partial^2 N}{\partial r^2} + \left[\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 D) - V\right]\frac{\partial N}{\partial r} - \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 V\right]N + \frac{\partial}{\partial \gamma}\left[\dot{\gamma}N\right] + Q, \tag{4}$$

where D and V are diffusion coefficient and advection velocity, respectively. Q is the source term, which includes two components here: rotational energy of magnetar and its magnetic energy.

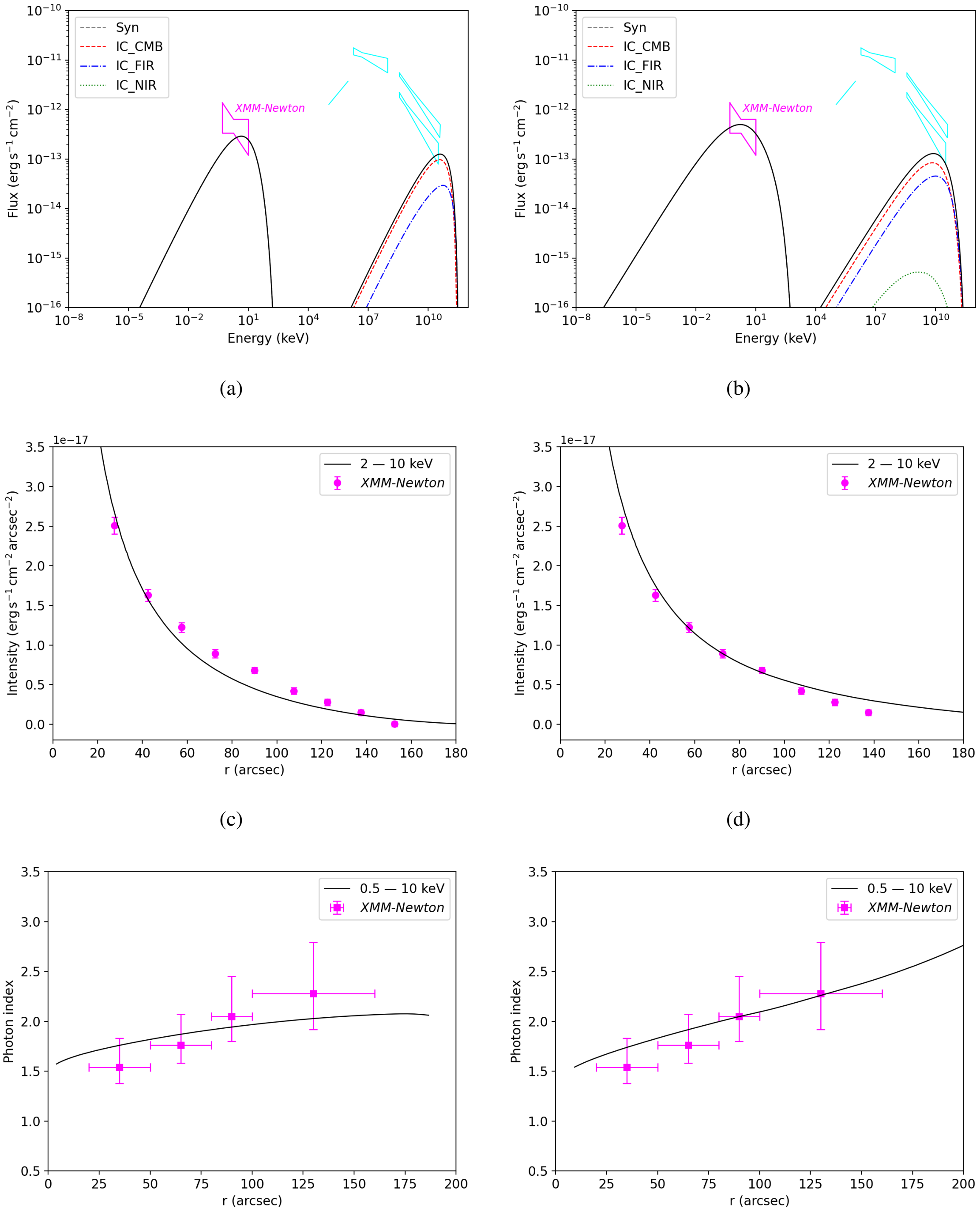
3. Application to Swift J1834.9-0846

The model described above is applied to the wind nebula of Swift J1834.9-0846. To investigate whether the MWN could be powered by rotational energy alone or another energy source is required, we discuss two different cases separately:

3.1 Case1: Powered by Magnetar Spinning-Down

In this case, the MWN is powered by the rotational energy of the magnetar, which is equivalent to the PWN. We apply our model to Swift J1834.9-0846 and calculate its multi-wavelength spectrum, X-ray intensity profile and photon index profile. The MCMC technique is employed to search for the best fitting results, which are shown in the left column in Figure 1.

It is clear that even the best fitting parameters in this case cannot explain the observations. The calculated synchrotron X-ray flux is about two times lower than the measured value, which means that rotational energy alone is not enough to power the observed MWN.



(a) (b)

(c) (d)

(e) (f)

Figure 1: The left column shows the best fitting results in the case where rotational energy is the only energy reservoir: spectrum of magnetar wind nebula around Swift J1834.9-0846 (upper), X-ray intensity profile (middle), Photon index profile (bottom). The right column is the best fitting results for the case where additional energy source is introduced.

3.2 Case2: Powered by Magnetar Spinning-Down and Magnetic Energy

Then we further considered the injection of the internal magnetic energy of magnetar in addition to the rotational energy. The best fitting results are shown in the right column in Figure 1. We can see that the spectrum, intensity profile and photon index profile could be simultaneously well explained in this case, which indicates that another energy source is required for the nebula of Swift J1834.9-0846.

The X-ray intensity profile and photon index profile are determined by the spatial distribution of the synchrotron emitting electrons, which is the result of the interplay of particle transport and cooling processes. Therefore, the radial distribution of the non-thermal photons could provide us valuable information about particle transport in MWN. In order to know whether particle transport is dominated by advection or diffusion, we calculated the particle advection timescale and diffusion timescale respectively, with the best fitting parameters. The ratio between them $r = t_{\rm adv}/t_{\rm diff}$, is about 0.003, which means that advection dominates particle transport in this nebula.

4. Conclusion

We simulated the X-ray emissions from the magnetar wind nebula around Swift J1834.9-0846 with different energy injection scenarios. We found that rotational energy alone is inadequate to account for the observed X-ray flux, while it could be well explained with the injection of magnetar's internal magnetic energy. In the latter case, advection plays a dominant role in particle transport in this nebula.

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